

DEVELOPMENT OF
A HYDRAULIC DYNAMOMETER

BY

S. W. THAL

ARMOUR INSTITUTE OF TECHNOLOGY

1917

621.43
T 32



Illinois Institute
of Technology
UNIVERSITY LIBRARIES

AT 475

Thal, S. W.

The development of a
hydraulic dynamometer



Digitized by the Internet Archive
in 2009 with funding from
CARLI: Consortium of Academic and Research Libraries in Illinois

THE DEVELOPMENT OF A HYDRAULIC DYNAMOMETER

A THESIS

PRESENTED BY

SAMUEL W. THAL

TO THE

PRESIDENT AND FACULTY

OF

ARMOUR INSTITUTE OF TECHNOLOGY

FOR THE DEGREE OF

BACHELOR OF SCIENCE

IN

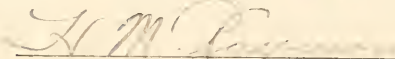
MECHANICAL ENGINEERING

MAY 31, 1917

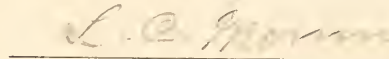
APPROVED:



Professor of Mechanical Engineering



Dean of Engineering Studies



Dean of Cultural Studies

ILLINOIS INSTITUTE OF TECHNOLOGY
PAUL V. GALVIN LIBRARY
35 WEST 33RD STREET
CHICAGO, IL 60616

Development Of A Hydraulic Dynamometer.

Preface.

In performing this thesis, the writer had in mind the development of an inexpensive though reliable piece of apparatus which may be used to good advantage in the testing of variable speed engines.

The writer is very grateful to Professor D. Roesch and Mr. H.G.D. Nutting for their assistance and advice concerning various problems that had to be solved during the carrying out of the work.

S.W.T.

Development Of A Hydraulic Dynamometer.

Table Of Contents.

Preface

Part I. General Survey Of Absorption Dynamometers.

I-I6

1. The Prony Brake. I.
2. Characteristics Of The Prony Brake. 2.
3. The Fan Dynamometer. 6.
4. Characteristics Of The Fan Dynamometer. 7.
5. The Electric Dtnamometer. IO.
6. Characteristics Of The Electric Dynamometer. II.
7. The Hydraulic Dynamometer. II.

Part 2. Description Of Test Apparatus. I6-3I.

Part 3. Brake Development. 3I-59.

1. Window Development. 3I.
2. Characteristics Of Brake With Smooth Discs. 36.
3. Development Of Discs. 43.
4. Characteristics Of Brake With Slotted Discs. 47.

Development Of A Hydraulic Dynamometer.

Table Of Contents.

Part 3. Brake Development.	31-59
5. Other Types Of Hydraulic Brakes.	53.
Part 4. Formulae For The Hydraulic Brake.	59-72.

Development Of A Hydraulic Dynamometer.

General Survey Of Absorption Dynamometers.

There are a number of methods by means of which the horsepower and performance of engines may be determined. The apparatus used in obtaining this information is termed a brake or a dynamometer. The absorption dynamometer is used for the purpose of absorbing power, or in a sense, for destroying the power developed by a given machine or engine.

Absorption dynamometers may again be subdivided into classes, depending on the manner in which they absorb power, or the medium by means of which they absorb this power.

The Prony or friction brake represents a class where the developed power is absorbed in overcoming friction between two members. These two members are the brake drum and the brake band. The brake drum is fastened to the shaft of the machine or engine to be tested. The brake band surrounds this drum, and adjustment is provided for, so that the friction between

Development Of A Hydraulic Dynamometer.

this band and drum may be varied to comply with the conditions desired. The brake drum is cooled by water which is sent into the hollow or center of the drum. The waste water is removed by another pipe which has a tendency to scoop up the water.

Characteristics Of The Prony Brake.

The operation of a Prony brake may be brought out or investigated from its characteristics. In order to show these characteristics of a prony or friction brake by means of curves, a series of runs were made with the brake band under different tension. A series of runs under these conditions would tend to coincide with the water dynamometer operating under different fillings of water. Only in two cases did we come near to a characteristic curve similar to that of the water brake. The curves were either straight lines or curves having abrupt turns. During the run at certain times the brake would tend to

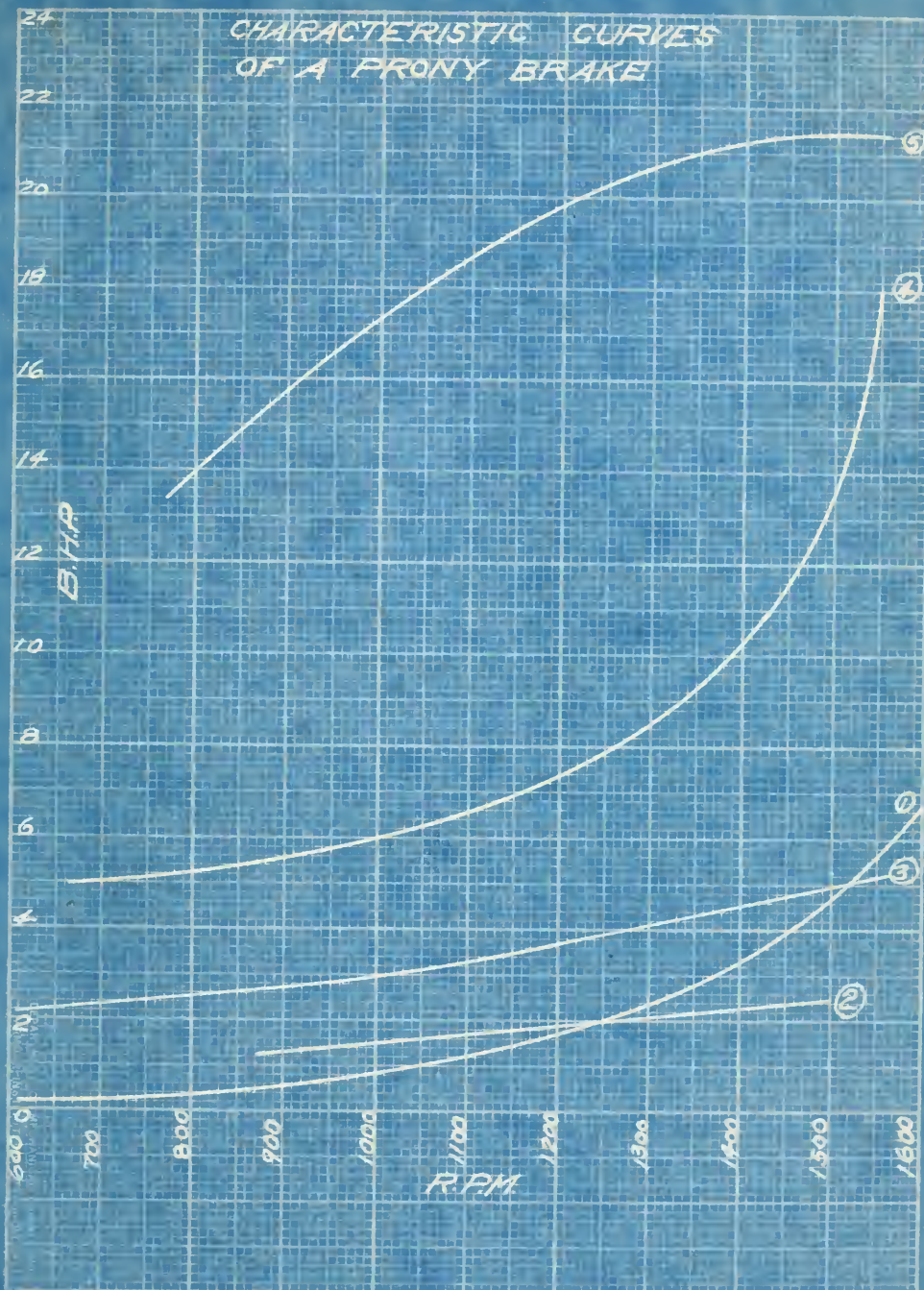
Development Of A Hydraulic Dynamometer.

bind and slow down the engine to the point where it would want to stop. The torque never had a definite value because of the bobbing up and down of the scale beam, caused by the intermittent binding and slipping of band on the drum. When the engine would miss fire in any of the cylinders, the brake would stop the engine.

CHARACTERISTICS OF A PRONY BRAKE OPERATING UNDER VARIOUS SETTINGS.

[illegible]

CHARACTERISTIC CURVES OF A PRONY BRAKE



Development Of A Hydraulic Dynamometer.

The fan dynamometer represents a type of dynamometer where the power developed by the engine is absorbed in overcoming the reaction between the air and a rotating impeller. The engine to be tested is placed in a frame. This frame is supported by two pedestals and is free to rotate about a horizontal axis. To the shaft of the engine under test is fastened the fan of the dynamometer. All other equipment, such as the cooling water system, must be mounted on the dynamometer frame. The engine is permitted to exhaust into the atmosphere because a pipe would offer a resistance to the dynamometer. By means of an arm and weights we are able to balance up the engine and frame previous to making any test. The torque is measured by a spring balance fastened to the end of an arm which is a part of the dynamometer frame. When the engine is in operation, the frame is caused to turn in the opposite direction of rotation of the engine. It is this reaction

Development Of A Hydraulic Dynamometer.

that is measured by the spring balance. The speed was recorded with a tachometer from the end of the fan shaft.

Characteristics Of The Fan Dynamometer.

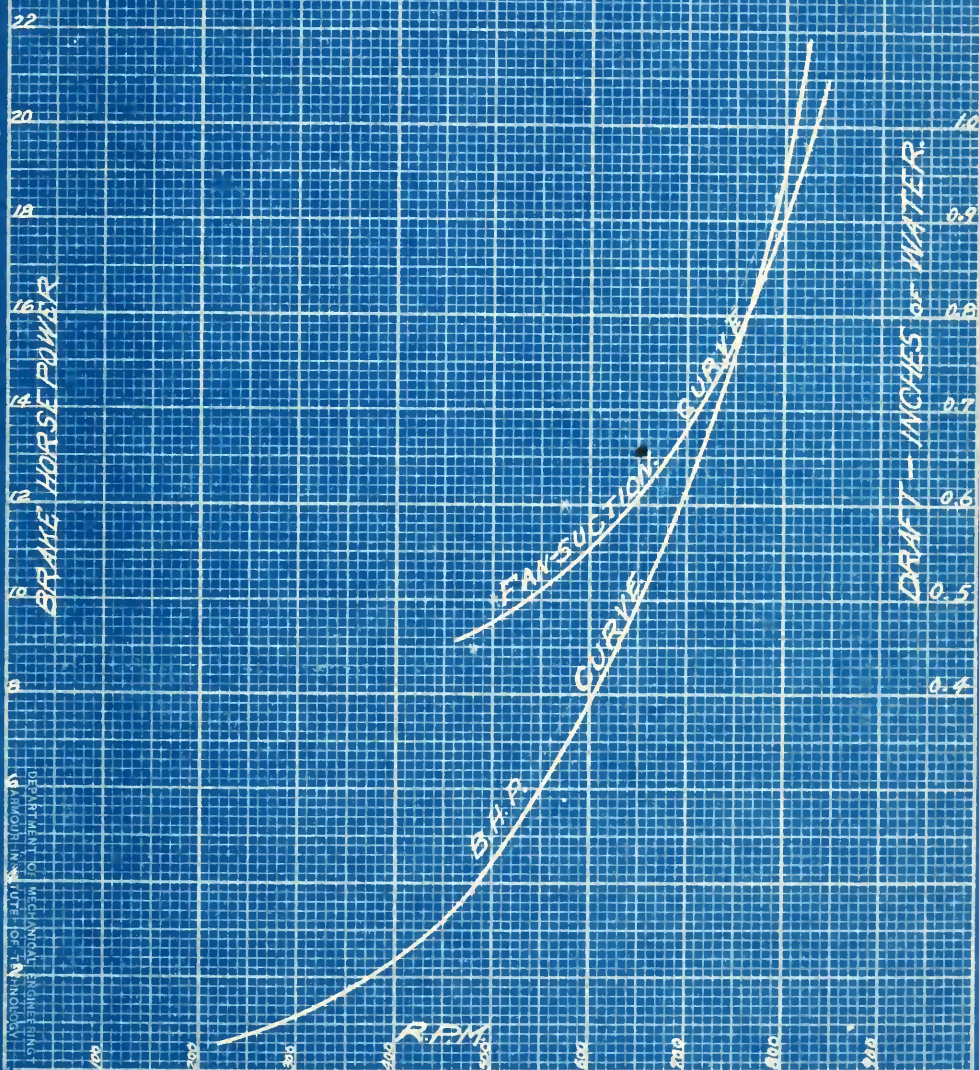
By means of a series of runs we were able to show the operation of the fan dynamometer in the form of a curve. The general form of the resulting curve was that of the curve in which the horsepower varied with the cube of the speed. The curve, showing the effect of speed on the suction behind the fan, took a form similar to that of the horsepower-speed curve.

A number of disadvantages of this type of dynamometer may be brought out. It is noticed that the exhaust gases are not piped to the outside of the test room for the reason previously mentioned. Thus these obnoxious odors are left in the test room to be inhaled by those present.

FAN DYNAMOMETER CHARACTERISTICS

<i>LBS. TORQUE</i>	<i>R.P.M.</i>	<i>B.H.P.</i>	<i>SUCTION OF FAN.</i>
53	820	21.7	.98
47	790	18.5	.89
43	740	15.9	.75
40	700	14.0	.61
32	640	10.3	.61
20	575	5.8	.60
18	500	4.5	.50
16	480	3.84	.45
14	450	3.15	—
10	355	1.8	—
5	192	0.5	—

CHARACTERISTICS OF FAN DYNAMOMETER



Development Of A Hydraulic Dynamometer.

One of the latest types of dynamometers is the electric dynamometer. This piece of apparatus in its fundamental form consists of a motor which may be run as a generator. The generator housing is supported on bearings held in two pedestals. A torque arm is fastened to this housing and to a scale of some form. When the armature of this generator is caused to rotate, we have an action of the generator produced which tends to turn the housing in the same direction as the driving shaft. Also a pull at a certain speed proportional to the developed power of the engine under test is produced in the dynamometer. By means of this pull we can determine the power developed. This type of dynamometer may also be used to start the engine and also to determine the power necessary to drive the engine or to overcome the internal friction or pumping effort of the engine. Although this type of dynamometer embodies the latest and best in dynamometer design, still it

Development Of A Hydraulic Dynamometer.
is considerably more expensive than any other
type of dynamometer.

Characteristics Of The Electric Dynamometer.

The several curves tend to show the characteristics and the effects of varying the operation of the electric dynamometer. These curves are the results of varying the resistance placed in the generator circuit. The form of all the curves are similar, and tend to follow the rule of the horsepower varying with the cube of the speed. The electric dynamometer like the fan and hydraulic types, does not tend to stop the engine when the engine slows down.

The hydraulic dynamometer belongs to that class of dynamometers where the power is absorbed by friction between the laminae of water as it moves between a series of rotating and stationary discs. The hydraulic dynamometer or water brake, as it is sometimes called, is made up of a barrel supported on roller bearings held by two pedestals. Within the barrel there is

5 SWITCHES			3 SWITCHES			1 SWITCH		
R.P.M	TORQUE	B.H.P.	R.P.M	TORQUE	B.H.P.	R.P.M	TORQUE	B.H.P.
420	22	2.3	500	17	2.1	360	18	1.6
590	28	4.1	790	25	4.9	670	30	5.1
725	36	6.5	1100	34	9.4	930	40	9.3
890	44	9.8	1430	44	15.7	1225	52	15.9
1180	58	17.1	1900	60	26.6	1460	63	23.0
1420	72	25.6	2250	73	41.1	1800	82	36.9
1750	91	39.8	2450	79	48.4	2150	100	53.8
1925	104	50						

CHARACTERISTICS OF THE ELECTRIC DYNAMOMETER.

CHARACTERISTIC CURVES OF THE ELECTRIC DYNAMOMETER

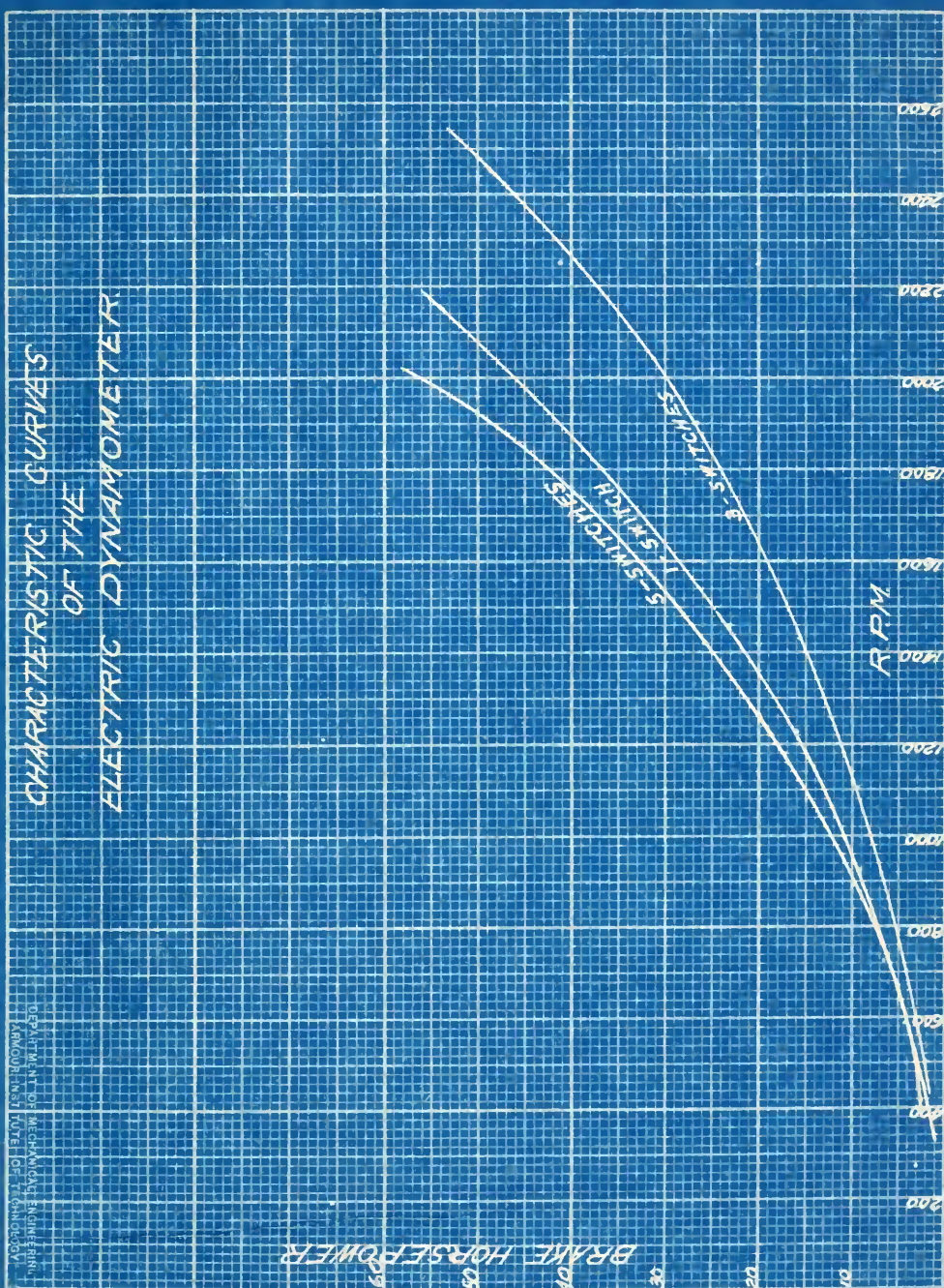
BRAKE HORSE-POWER

R.P.M.

5-5 KITCHES

3-3 KITCHES

ACCORDING TO THE 1200 TEST POWER
THESE CURVES WERE OBTAINED



Development Of A Hydraulic Dynamometer.

a shaft to which are fastened the rotary discs. Each rotary disc moves in its own compartment determined by the spacing of the stationary discs. Water is admitted into the brake through the side of the barrel, and is circulated to the various compartments by the rotating of the discs. The water is removed from the barrel through a discharge pipe in the bottom. Water is admitted to the barrel and removed from it in sufficient quantity to prevent formation of steam and heating of the dynamometer. By varying the amount of water in the barrel, we vary the load placed on the engine under test. By means of a torque arm, connecting the barrel to a scale of some sort, we are able to determine the pull on the scale for a given length of arm.

The hydraulic dynamometer is an inexpensive type of brake, and although we are not able to determine the internal friction of the engine by means of it, nevertheless we can determine very accurately the power actually developed by

Development Of A Hydraulic Dynamometer.
the engine at the shaft.

There are a number of water brakes which are modifications of the hydraulic brake and of the Prony brake.

It is the hydraulic type of dynamometer that was used in the carrying out of this thesis. The construction and details of this brake, together with the procedure is given in the pages that are to follow.

Development Of A Hydraulic Dynamometer.

Description Of The Apparatus.

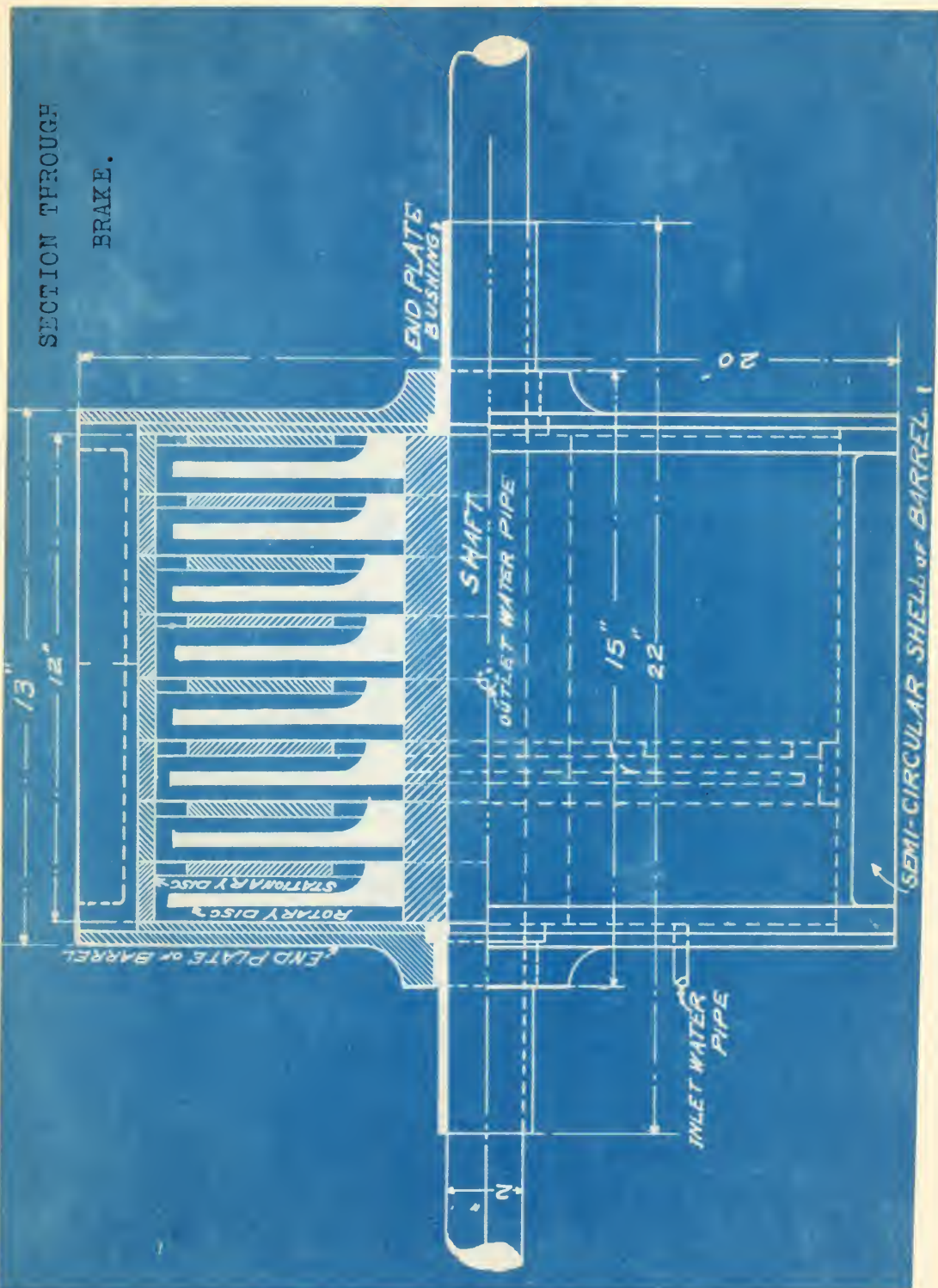
The dynamometer that was used in the investigation was designed by Professor G.F. Gebhardt, Professor of Mechanical Engineering, Armour Institute Of Technology.

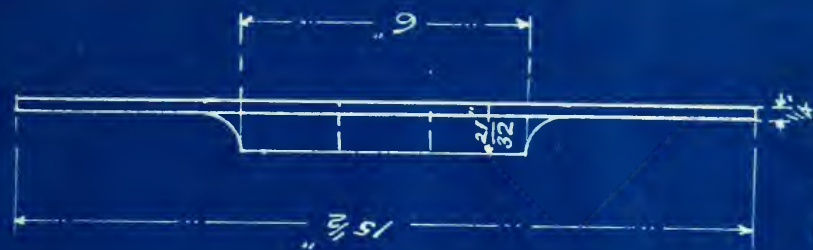
The drum or barrel of the dynamometer was made up of two end plates 20" in diameter. The sides of the barrel consisted of two semi-cylindrical pieces flanged together along a longitudinal joint and also fastened to the end plates with a flange. The end plates were reamed so that brass bushings could be pressed into them.

The compartments, previously mentioned, were made up by spacing eight stationary discs at the desired distance so as to allow for the free rotation of the rotary discs. These stationary discs were clamped in place by the two semi-circular parts of the barrel which encircled them.



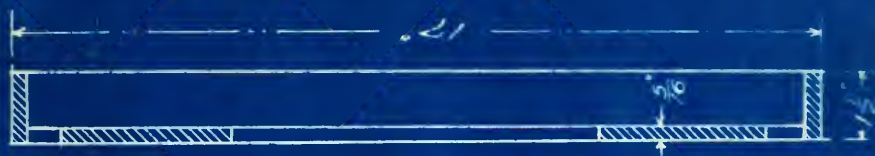
SECTION THROUGH BRAKE.





Rotary Discs.— 8 Used — Brass.
Previous To Slitting

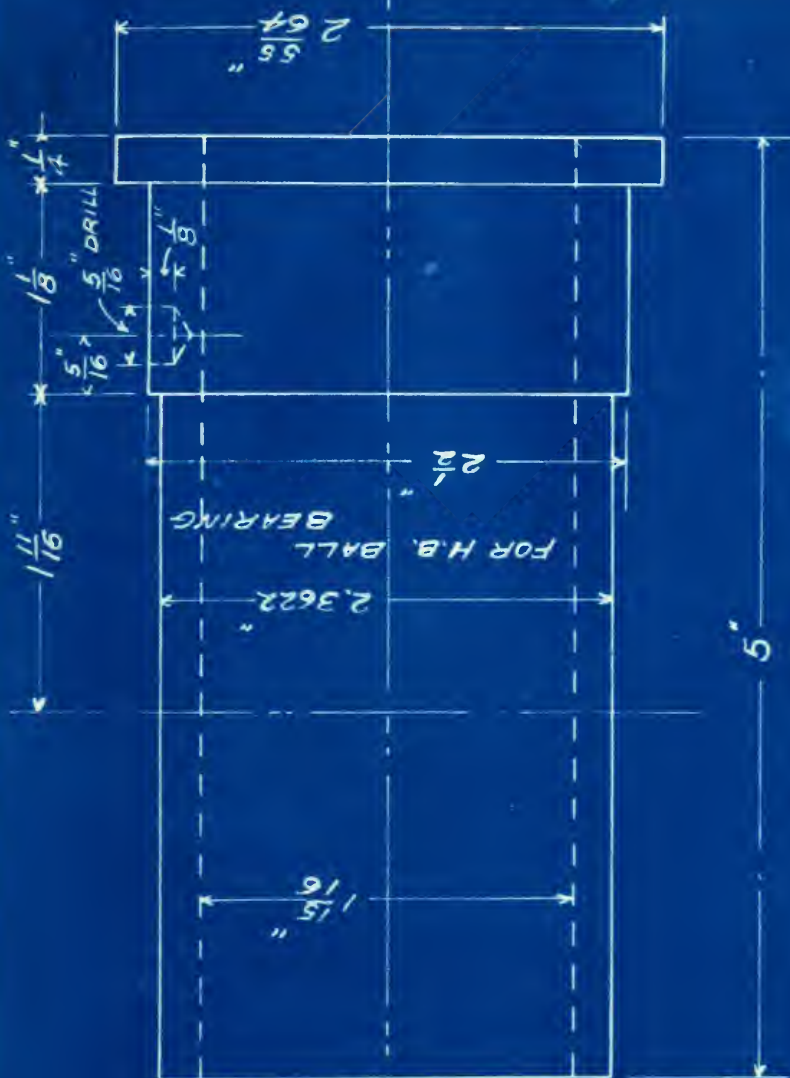




Stationary Disc - 8 Used. C.I.
Previous To Slotting

Development Of A Hydraulic Dynamometer.

The stationary discs forming these compartments were made of cast iron. They were so designed as to have a rim and a wall which would tend to form three sides of the compartment. In the wall of this disc was a hole large enough to permit the hub of the rotary disc to project through. Small elliptical holes, near the rim of the stationary disc, permitted the water to circulate from one compartment to the other and thus have the same amount of water in all compartments. The rotary discs, of which there were eight in number, were machined from cast brass. These were then turned to size and polished. Set screws placed 90 degrees to each other were used to hold the disc tight to the dynamometer shaft. These rotary discs were placed on the shaft, so that the distance from the stationary discs was the same on both sides thus giving an equal amount of water on each side of the discs. The shaft carrying these discs projected through the brass bushings in the end plates. One end of this shaft had a key slot in



BEARING FOR WATER BRAKE.
MAKE 2. BEARING BRASS.

Development Of A Hydraulic Dynamometer.

it so as to hold a coupling. Also small holes were spotted in the shaft to hold the set screws which would prevent longitudinal movement of the coupling.

The brass bushings in the end plates projected somewhat beyond the end plates so that they could pass through ball bearings which were held in pedestals. These bearings allowed the dynamometer to rotate freely with as small a loss of torque as possible. Attention may be called to the method of mounting the dynamometer barrel in the pedestal bearings. By so designing this arrangement we eliminate the loss of torque or power which would otherwise be consumed by the shaft if it rotated in the pedestal bearings.

The supply water was admitted to the barrel of the dynamometer by means of a 1/2" pipe tapped into the side or end plate of the barrel. By means of a control valve we were

Development Of A Hydraulic Dynamometer.

able to supply the desired amount of water to the barrel. A 1/2" pipe was also tapped into the bottom of the barrel to allow for a constant flow of water from the barrel and thus prevent heating within the dynamometer. A control valve was inserted in the discharge line so that by means of the two valves we were able to get a fine adjustment of the flow of water through the barrel. A relief valve was placed at the top of the barrel to permit all the air to be removed from the barrel. The torque arm was bolted to the outer side of the barrel. An eye bolt placed in the end of this arm, 26.25" from the center of the shaft, permitted connection to be made to a spring balance. The barrel and apparatus were balanced at no load by means of an arm placed on the side of the barrel opposite to that on which the torque arm was fastened. By means of weights placed on this arm a perfect balance of parts was obtained.



Development Of A Hydraulic Dynamometer.

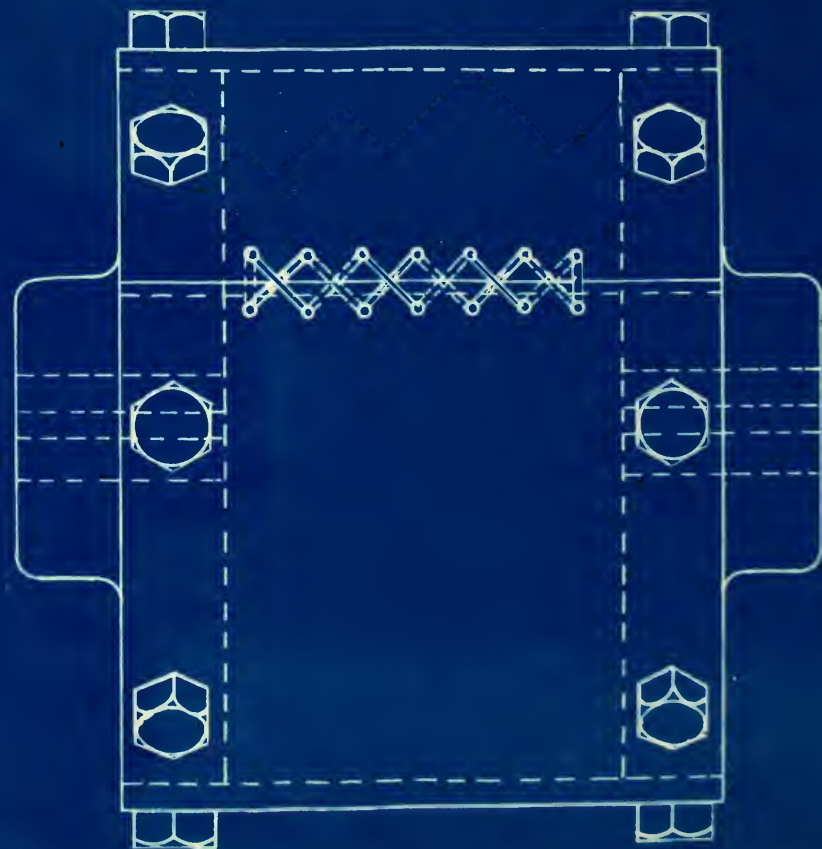
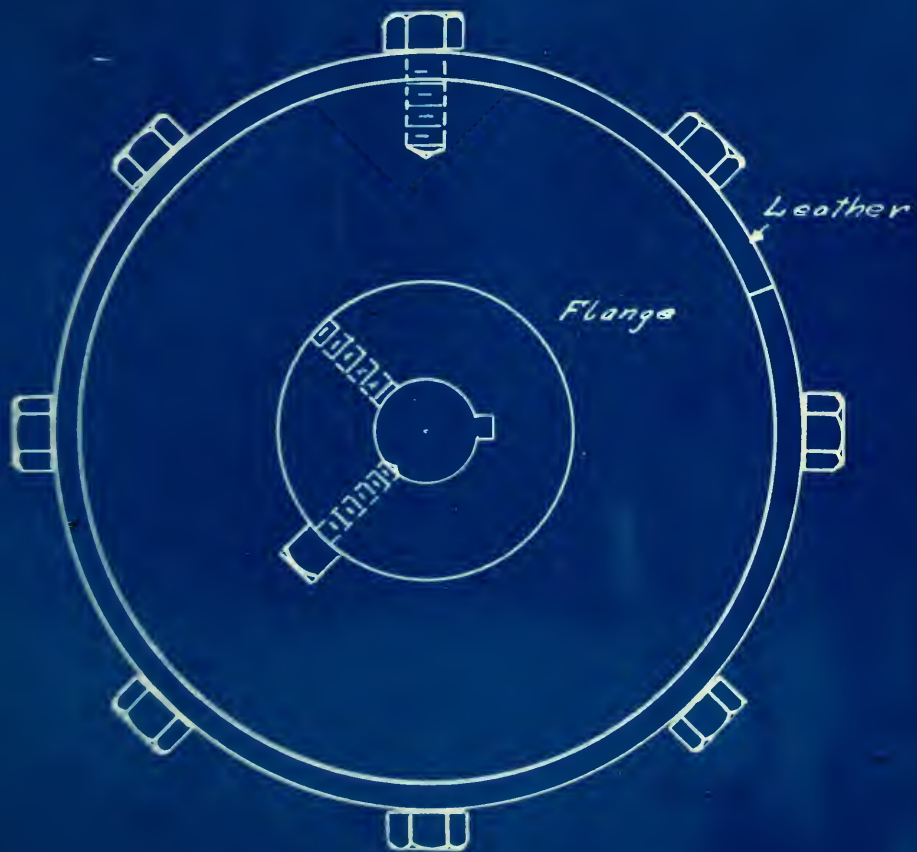
The power for making the initial test or investigation of the brake was supplied by a Ford automobile engine. This engine was mounted on cast iron stands. The dynamometer was placed on a concrete base and fastened to the engine with a flexible leather coupling specially built for this test. The leather coupling was made up of two cast iron flanges drilled out and keyed to the shafting of the engine and dynamometer. Around the periphery of these flanges and spaced evenly apart, were eight $\frac{3}{8}$ " tapped holes. A piece of leather about 7" wide and 23" long was wrapped around the circumference of these flanges, and holes corresponding to those in the flanges were punched in the leather. By means of $\frac{3}{8}$ " cap screws and washers the leather was fastened to the flanges, and a good flexible coupling was obtained.

The speed of the engine was obtained from a speedometer which recorded in miles



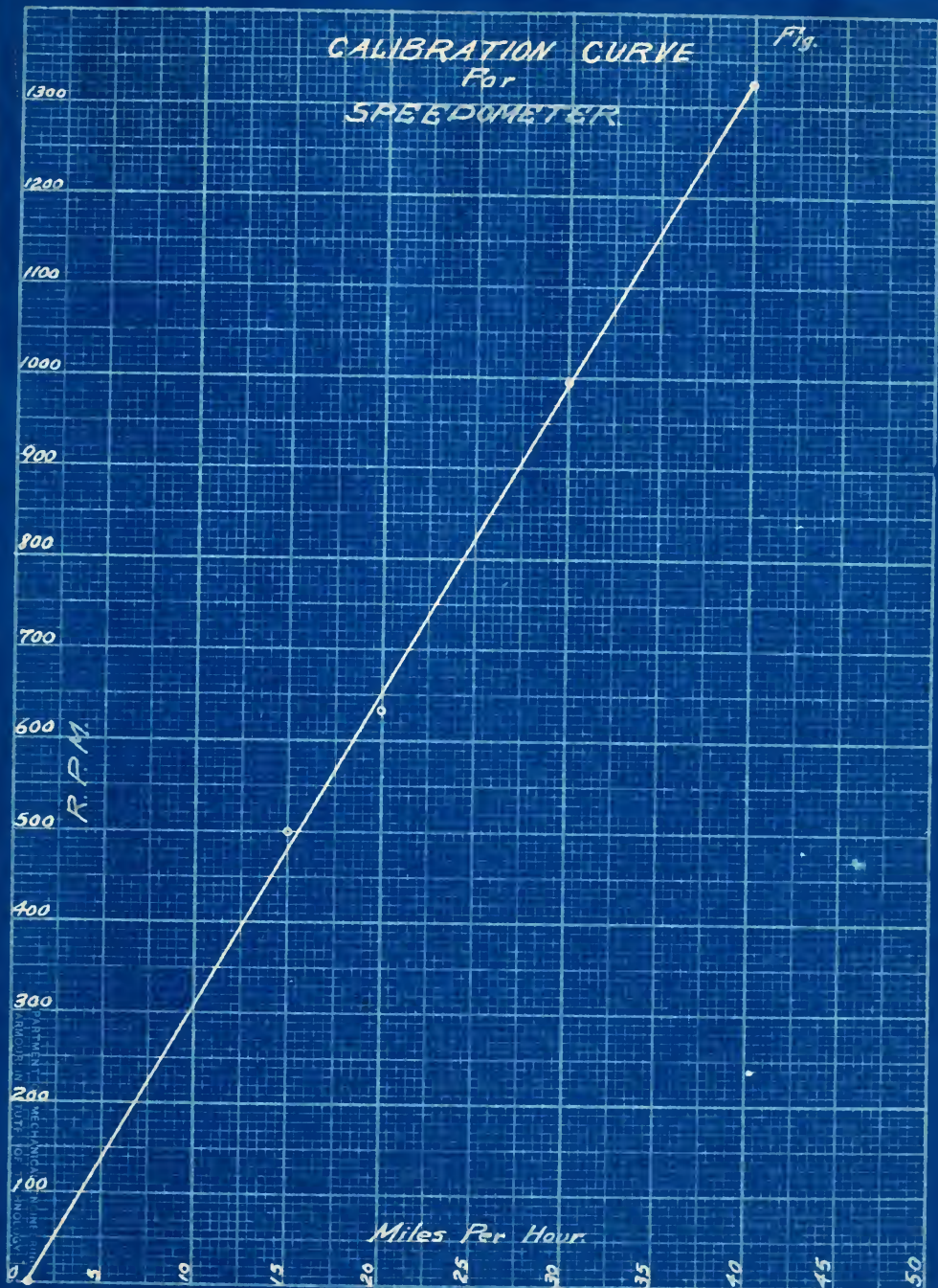


FLEXIBLE COUPLING BETWEEN ENGINE AND BRAKE.



CALIBRATION
OF
SPEEDOMETER

MILES PER HOUR	R.P.M.	AVERAGE R.P.M.
20	636	
20	633	637
20	641	
30	988	
30	999	994
30	995	
40	1329	1325
40	1320	



Development Of A Hydraulic Dynamometer.

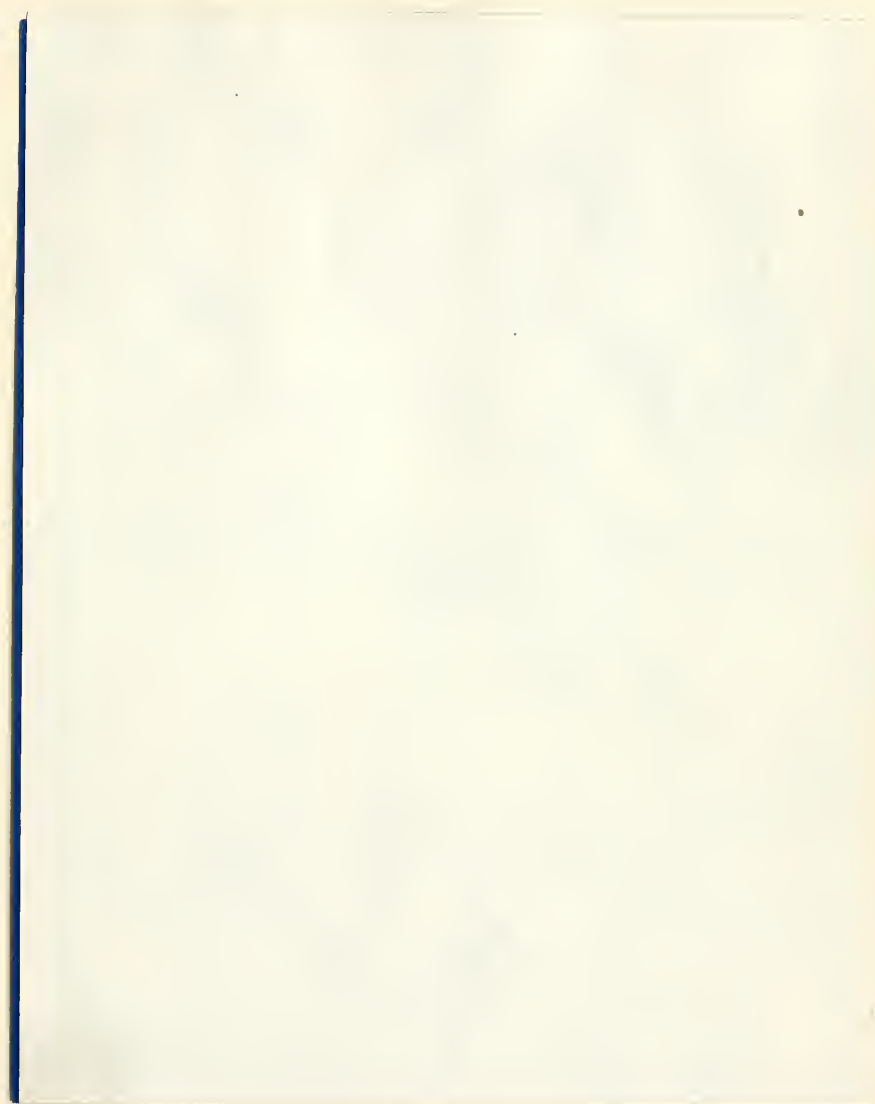
per hour. This speedometer was calibrated so that the readings in R.P.M. could be obtained. The speedometer gearing was taken from the flange on the coupling, and by means of a one to one gear ratio we obtained a speed of the speedometer shaft equal to that of the dynamometer shaft; therefore the speed of the in accordance with that of the speedometer.

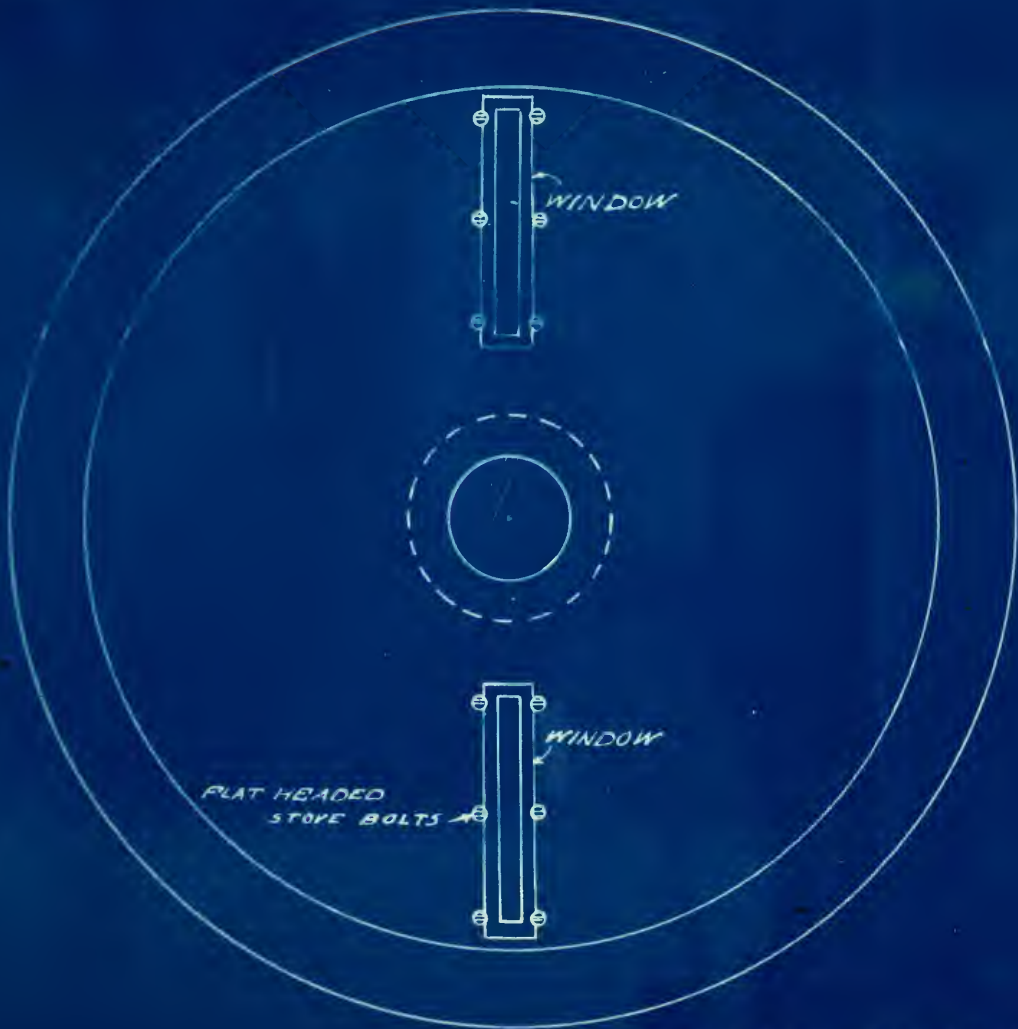
Development Of A Hydraulic Dynamometer.

Brake Development.

The apparatus was set up in running order. Then the problem of accurately determining the amount of water in the barrel was next to be solved. At first a number of holes were drilled at various distances from the center of the barrel in the end plate. In order to determine the level of the water in the barrel these plugs were removed in turn until the water issued forth. This was then considered the level of the water. This is not exactly correct, because the water in the dynamometer is in the form of a spray at the inner edge of the water ring, which formed in the barrel when the discs were in motion. Some times the water would come through the holes by being sprayed up to the hole, and this would not represent the correct position of the water in the barrel.

Then the idea of placing windows in the end plate of the barrel was put into effect. The plate was removed from the dynamometer; and by





END PLATE OF DYNAMOMETER BARREL.
SHOWING OBSERVATION WINDOWS.



Development Of A Hydraulic Dynamometer.

means of a milling machine, slots, about $1\frac{1}{2}$ " wide and 5" long, were cut through the plate. Next a gasket of rubber was cut so that it would surround this slot and still permit the slot to be clearly observed. A metal plate of the same shape as the rubber gasket was made; and by means of bolts tapped into the end plate , we were able to hold the piece of plate glass against the end plate and still have a water tight joint. Although the action of the water within the barrel could now be seen very clearly, still the water took the form of a spray as it passed the windows. It is to be noticed that these window slots left sharp edges on the inner side of the end plate. As the water passed these slots it would have a tendency to spray and whirl and also to rise in the slots. Thus we had conditions which were not reliable, so far as securing the correct amount of water in the barrel was concerned. The next step was to have the surface of the windows

Development Of A Hydraulic Dynamometer.

flush or even with the inner side of the end plate. Again the plate was removed, and a recess was cut in the plate on the inner side. This recess was made to fit a piece of plate glass 1" wide and 5 1/2" long and 3/8 inch thick, when the glass was placed on top of a cardboard gasket. Then some flat-headed stove bolts were used to hold the glass in place. The glass and the end plate were then drilled so as to allow these stove bolts to be countersunk and flush with the inner surface of the plate. This seemed to give the desired results. The water in the dynamometer could now be seen clearly. The eddying and spraying caused by the water striking the slot edges had been done away with. The ring of water had now taken a definite shape and width. Also this ring of water seemed to have practically the same width at the top as at the bottom of the barrel, although there was a slight difference due to the effect of gravity on the mass of water.

Development Of A Hydraulic Dynamometer.

Characteristics Of The Brake With Smooth Discs.

The dynamometer and apparatus were now ready to be used for obtaining the characteristics of the brake under various fillings of water and at various speeds. From the data obtained and the curves plotted we can see the range of operation of this dynamometer with smooth discs. We notice that with a small filling of water the horsepower transmitted is small and the speed is large. Even with the barrel completely filled with water we find that the power absorbed is small at that the speeds are high.

In testing automobile engines, especially when running with wide open throttle, it would be destructive to the engine and apparatus to permit any high speeds for any considerable length of time. Thus in order to stay within a reasonable range of speeds we would not be able to obtain the maximum power that the engine would be capable of developing. From information received concerning the operation

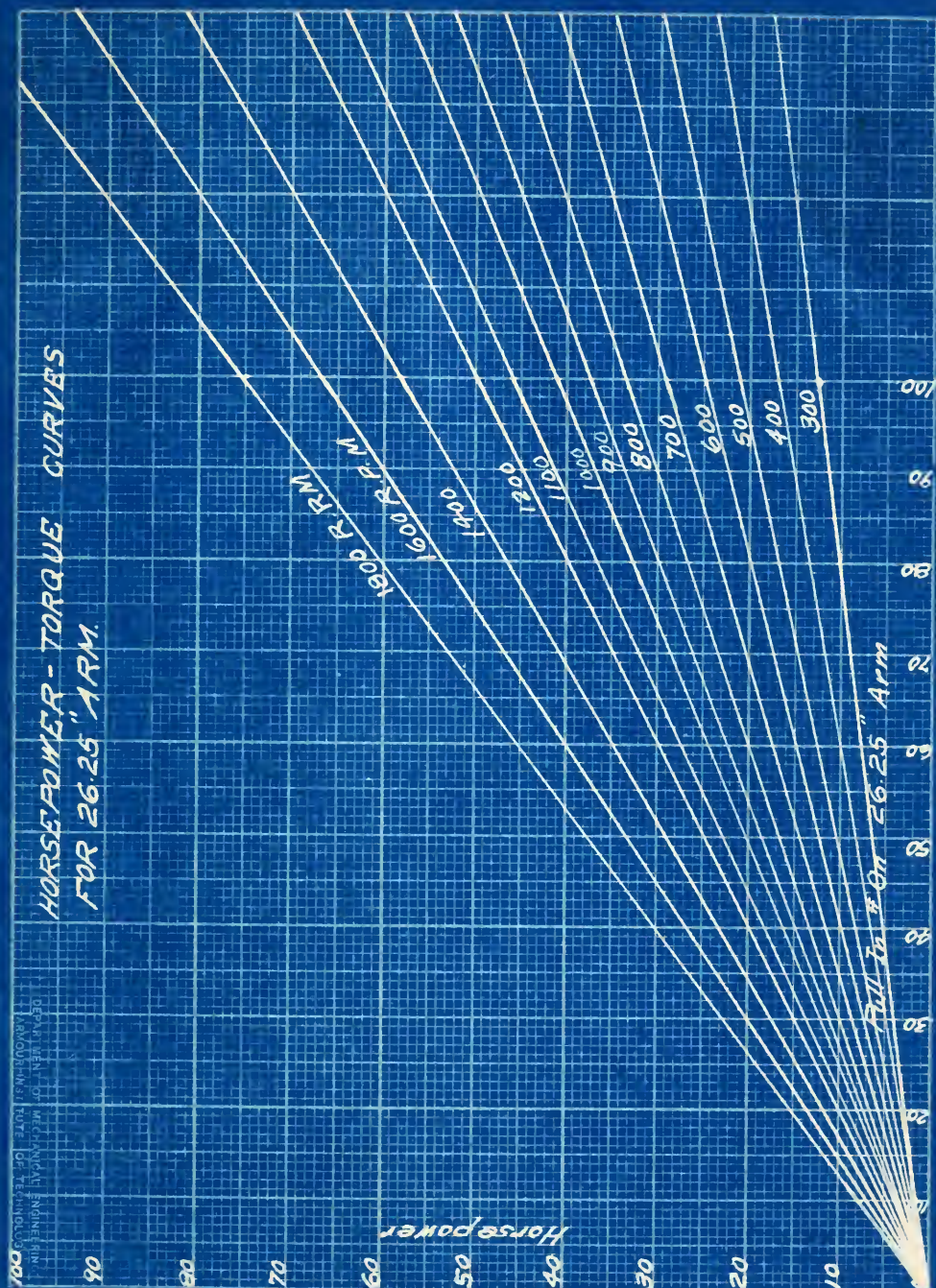
CHARACTERISTICS OF WATER DYNAMOMETER.

B.H.P.	R.R.M.	ACTUAL TORQUE	# CALCULATED TORQUE	COEFFICIENT OF FRICTION-f
$R_0 = 7.75"$ $R_I = 3.813$ NO.1				
1.74	520	8	7.65	.0047
3.1	665	11	12.5	.00396
5.3	795	16	17.8	.00404
10.75	990	26	27.6	.00428
11.9	1020	28	29.3	.00429
$R_0 = 7.75"$ $R_I = 4.5"$ NO. 2				
1.99	530	9	7.5	.0054
3.56	710	12	13.4	.00404
6.4	815	18	17.7	.00467
11.2	990	27	26.2	.00465
$R_0 = 7.75"$ $R_I = 5.25"$ NO.3.				
2.05	545	9	7.05	.0056
3.66	730	12	12.6	.00585
7.14	900	19	19.3	.00442
10.0	1040	23	24.6	.00404
$R_0 = 7.75"$ $R_I = 6.5$ NO.4.				
1.66	530	7.5	4.3	.00795
3.74	745	12	8.4	.00645
5.34	850	15	11	.00615
9.4	1020	22	15.8	.00625
$R_0 = 7.75"$ $R_I = 7"$ NO.5.				
1.65	565	7	3.1	.0082
3.09	740	10	5.5	.0088
3.98	795	12	6.3	.0083
7.45	990	18	9.8	.0102

CHARACTERISTICS OF WATER DYNAMOMETER.

Barrel Full of Water. NO. 6.				
B.H.P	R.P.M	ACTUAL TORQUE	CALCULATED TORQUE	COEFFICIENT OF FRICTION-f
3.53	650	13	12	.00486
5.65	750	18	16	.0051
8.67	900	23	23	.0045
11.5	980	28	27.2	.00465
14.6	1060	33	31.8	.00465
15.7	1075	35	32.8	.0048
			Average-f=	.00473

HORSEPOWER - TORQUE CURVES FOR 26.25" ARM.



Development Of A Hydraulic Dynamometer.
of this dynamometer at a previous date, as high as 75 horsepower were placed on the brake with an accompanying speed of 3000 R/P/M.

There are other points, concerning the operation of this brake under the above stated conditions, that may be mentioned. When the engine happened to drop in power because of a change in the carburetor mixture or missing fire in the cylinders, the brake did not tend to stop the engine or place an excessive load on the engine. The torque or resisting moment of the brake varies with the square of speed, and unlike the action of the friction prony brake it allows the engine to vary in speed without an enlarged variation in torque. This brake was capable of holding a constant torque and speed for a considerable period without any adjustments being made to the inlet or discharge control valves. Thus we can see how a brake of this type can be

Development Of A Hydraulic Dynamometer.
used, when a test with constant speed and torque is desired.

The amount of water in the dynamometer barrel was measured and mentioned on the curves in terms of a ring of water. The curves obtained from the data taken with the smooth discs are represented by the broken line curves. The diameter of the rotating discs, as we can see from the blueprint is 15.5#inches. Now we allow water to enter the barrel while these discs are in motion. We then control the supply until the ring of water caused by the action of the centrifugal force is at the width desired from the outer periphery of the rotating disc. The width of the ring is the dimension given on the curve as, 1" ring, 3" ring etc. When the dynamometer was full of water we still have a ring formed. The width of this ring is determined by the hole in the stationary discs which 7.625" in diameter. Besides this ring that formed and caused a

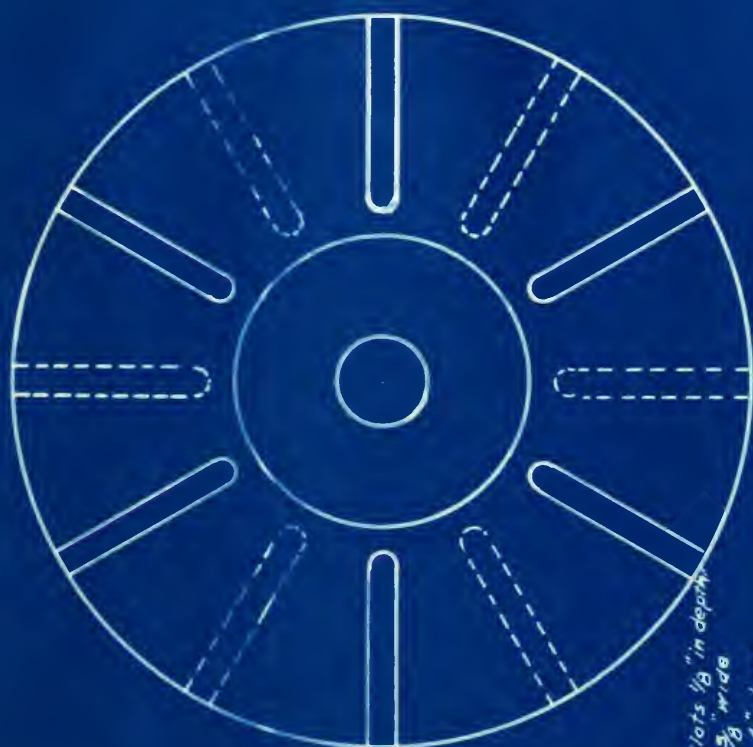
Development Of A Hydraulic Dynamometer.

resistance to the load when operating under a full barrel of water we have the action of the filling of the water at the hubs of the rotating discs. The rotating discs are $5/16$ " wide. There is a resistance caused by the water action on this area of the periphery of the rotating discs which causes an increase on the scale reading. This reaction due to this area is not considered in the formula which is derived in another section.

Development Of A Hydraulic Dynamometer.

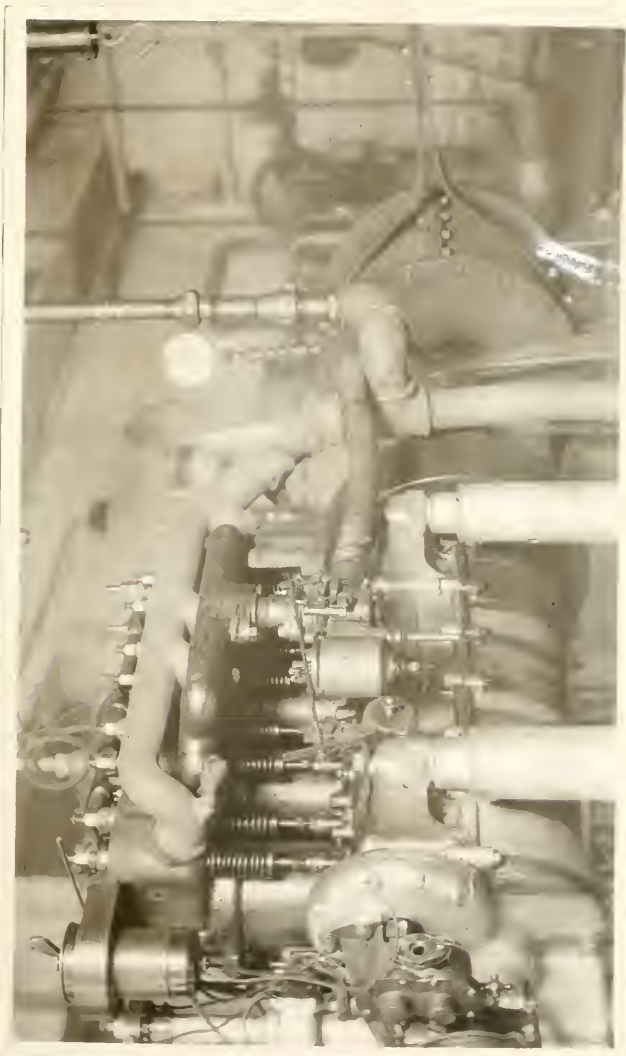
Development Of The Discs.

It was observed from the test that the speed was too high for the power transmitted. Attention was next given to a method of development by means of which we would be able to hold a greater load with the same number of discs at a lower speed. The idea of increasing the resistance of the discs by slotting them was then taken up. The revolving discs and also the stationary discs were then removed from the dynamometer. Jigs had to be constructed for the purpose of slotting these discs on the milling machine. These discs were so constructed that they would fit the slots of the milling machine carriage and also allow the discs to be revolved about a fixed center when changing the discs for slotting. These jigs also decreased the time of cutting the slots. Six slots were cut on each side of all the discs. The slots were made 4" long, $\frac{5}{8}$ " wide and $\frac{1}{8}$ " deep.

METHOD OF SLOTTING DISCS

Development Of A Hydraulic Dynamometer.

The dynamometer was again assembled. This time a Rutenber engine of a larger power than the Ford engine was used for the tests. The dynamometer was placed on a base constructed from timbers and held together with lag bolts. The foundation was then anchored to the floor with bolts.



Development Of A Hydraulic Dynamometer.

Characteristics Of The Brake With Slotted Discs.

A test, similar to the initial investigation was then made. The data and curves as plotted for this run showed that by slotting the discs we were able to absorb as high as 29 horsepower at a speed of about 1300 R.P.M. This was done with the dynamometer barrel full of water so that a 2" ring was formed in the barrel between the discs. When operating so that the barrel was completely filled with water we were able to hold 27 horsepower at a speed of 1000 R.P.M. Previous to slotting the discs we were able to hold only about 12 horsepower at this speed. This represents an increase of 15 horsepower due to slotting the discs.

The dynamometer also seemed to operate with less vibration than before. A finer adjustment of speed was obtained for a given torque. The curves, plotted from the data obtained, show that after a speed of 850 R.P.M. was reached,

CHARACTERISTICS OF WATER DYNAMOMETER AFTER DEVELOPMENT OF BLADES.

1" RING				2" RING				3" RING			
T.	R.P.M.	H.P.	f	T.	R.P.M.	H.P.	f	T.	R.P.M.	H.P.	f.
5	364	.76	.0135	8	435	1.45	.0091	8	400	1.33	.0088
8	545	1.81	.0096	13	570	3.08	.0083	13	500	2.7	.0091
11	710	3.24	.0078	16	650	4.33	.0082	18	590	4.42	.0090
12	765	3.81	.0073	22	750	6.85	.0085	23	665	6.37	.0091
14	810	4.72	.0076	28	850	9.9	.0084	28	700	8.15	.0099
18	945	7.08	.0072	35	950	13.8	.0084	33	770	10.6	.0098
21	1130	9.85	.0059	39	1040	16.9	.0078	41	870	14.8	.0095
29	1280	15.5	.0063	45	1200	22.5	.0075	46	910	17.4	.0097
30	1415	17.6	.0054	50	1260	26.2	.0068	49	970	19.8	.0091
35	1475	21.4	.0057	53	1310	28.8	.0067	53	975	21.5	.0098
								57	1015	24.1	.0097
								61	1065	27	.0094

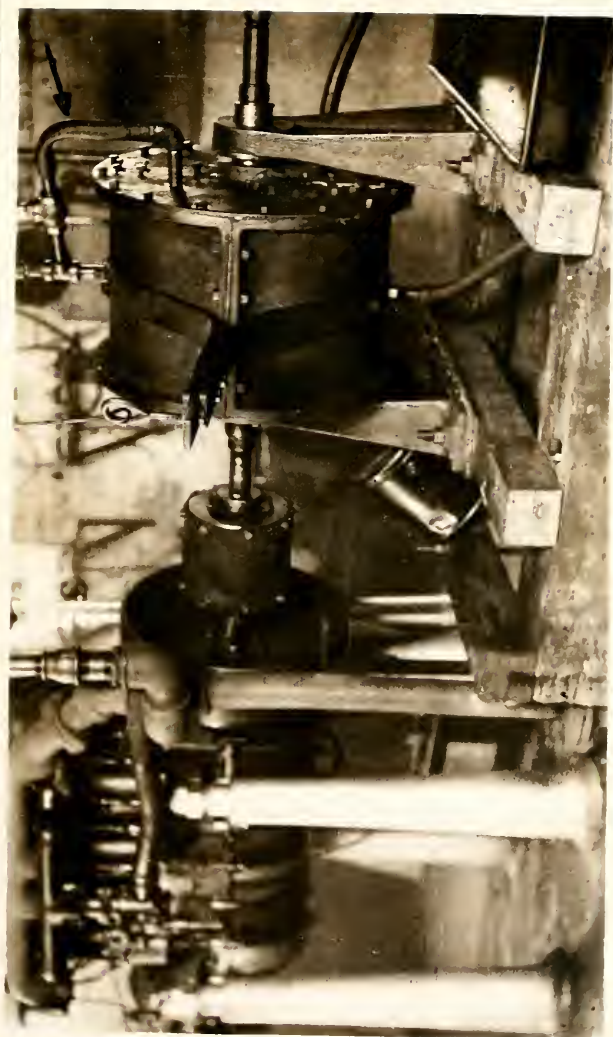
CHARACTERISTICS OF WATER
DYNAMOMETER AFTER DEVELOPMENT OF BLADES.

4" RING				BARREL FULL.			
T.	R.P.M.	H.P.	ξ	T.	R.P.M.	H.P.	ξ
12	450	2.24	.0094	8	350	1.16	.0104
25	660	6.85	.0091	18	530	3.96	.0102
32	725	9.65	.0097	21	580	5.06	.0100
45	870	16.3	.0095	26	640	6.9	.0101
52	940	20.3	.0094	32	710	9.45	.0101
56	960	22.3	.0097	37	775	11.9	.0099
57	990	23.4	.0093	40	810	13.5	.0098
58	1000	24.1	.0092	51	910	19.3	.0099
63	1030	27.	.0094	54	950	21.3	.0096
				64	1020	27.2	.0098

Development Of A Hydraulic Dynamometer.

the horsepower absorbed by the brake increased in almost the same proportion as the speed. This was for a complete filling of the barrel.

By comparing the sets of curves for the brake, before and after developing the discs, we can see the effect of slotting the discs. Still there are other lines along which this brake may be developed. At first it was thought, that by making use of the difference of pressures between the center and outer circumference of the barrel, we could increase the resistance of the dynamometer. A pipe with a control valve in the line was next placed on the dynamometer so that the outer edge of the barrel was connected to the center of the barrel. By means of this connection it was thought that we could use the water, now under pressure to advantage at the center of the barrel. A run was made with this connection free to allow the circulation of the water. No change of results could be seen. Possibly this



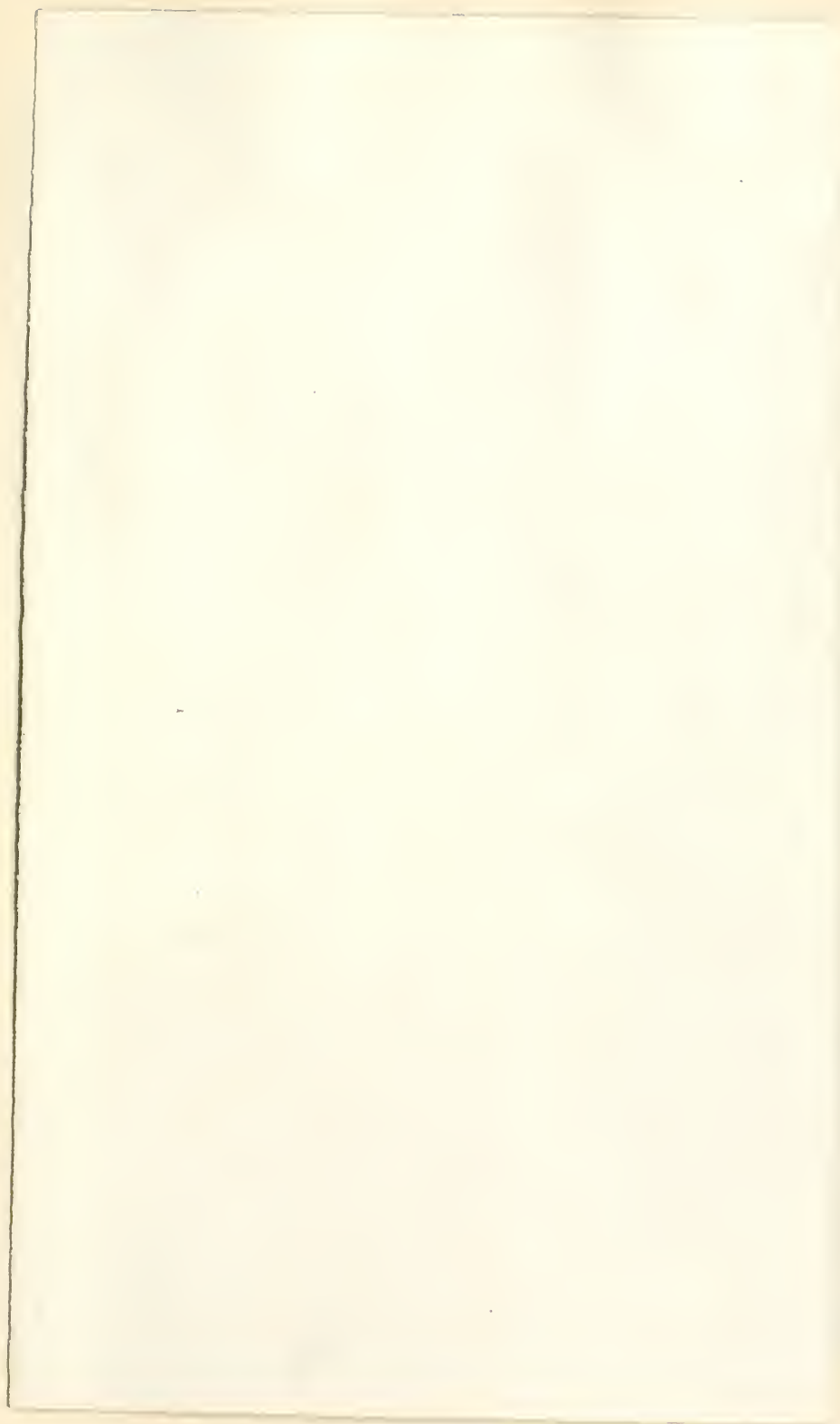
Development Of A Hydraulic Dynamometer.

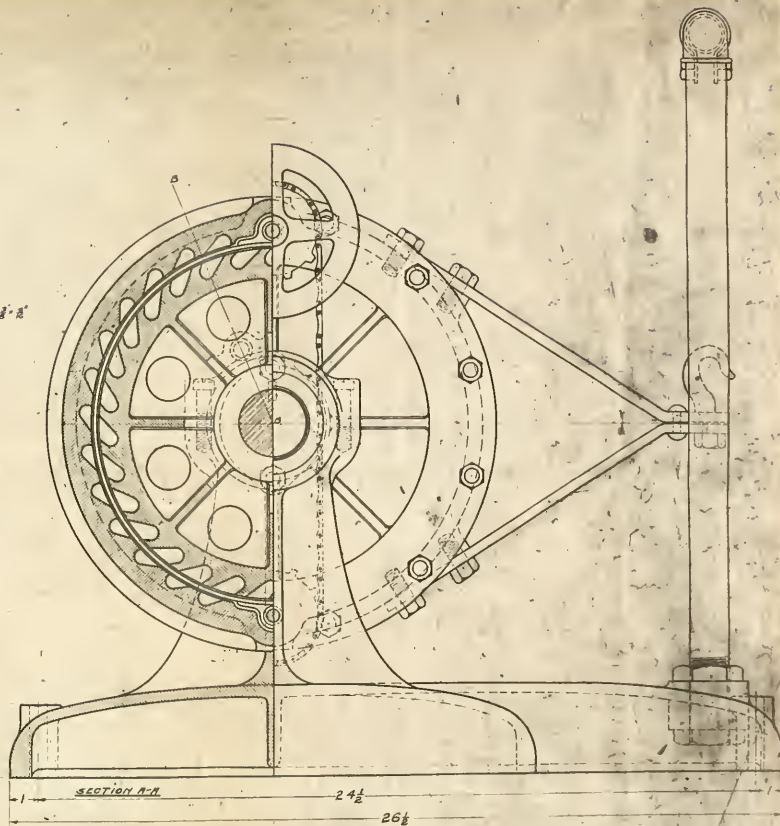
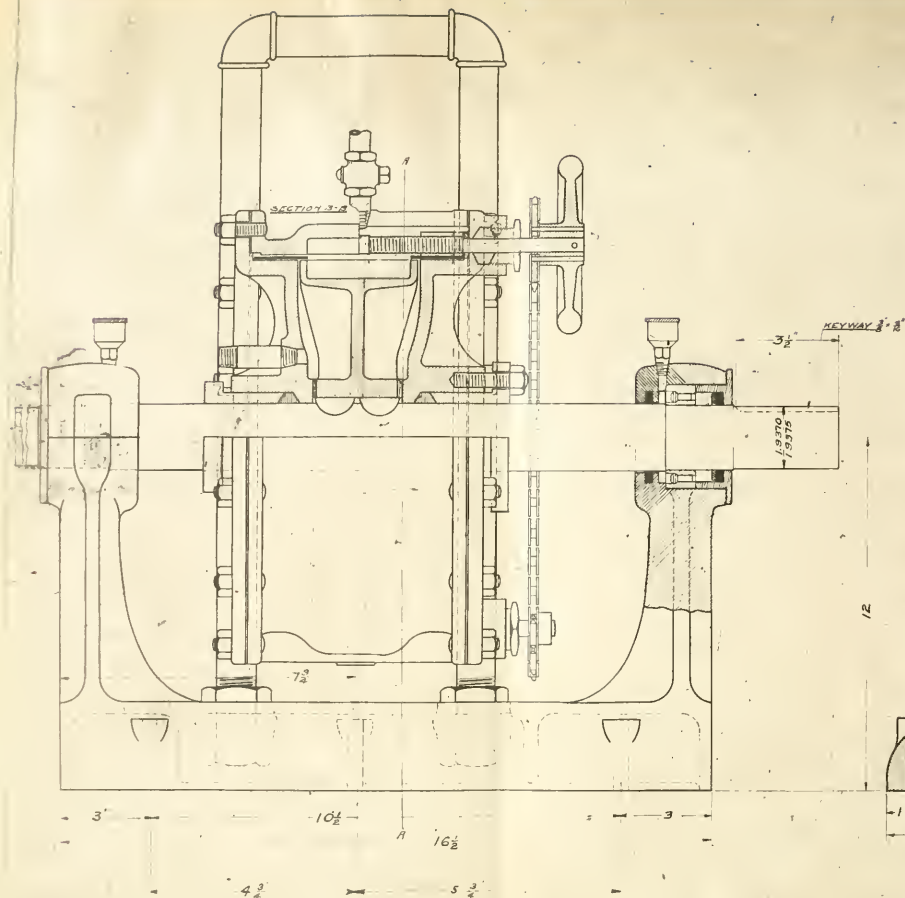
was due to the small size of pipe used($1/2''$), in proportion to the amount of the water in the barrel. Thus we can see that we must look to other methods of development in both the discs and the dynamometer barrel. In order to increase the power absorbing capacity of this dynamometer it would be necessary to further increase the resistance of the discs. This could be accomplished by cutting more slots on the faces of the discs and also by slotting the outer periphery of the revolving discs. There would be a limit to the method of slotting these discs because of the liability of distortion or breakage. Vanes or scoops could be fastened to the faces of both the revolving and stationary discs in such a manner as to form an inefficient centrifugal pump. Another improvement, which may tend to increase the proper distribution of the water in the various compartments, would be to supply each compartment with a separate supply and discharge pipe.

Development Of A Hydraulic Dynamometer.

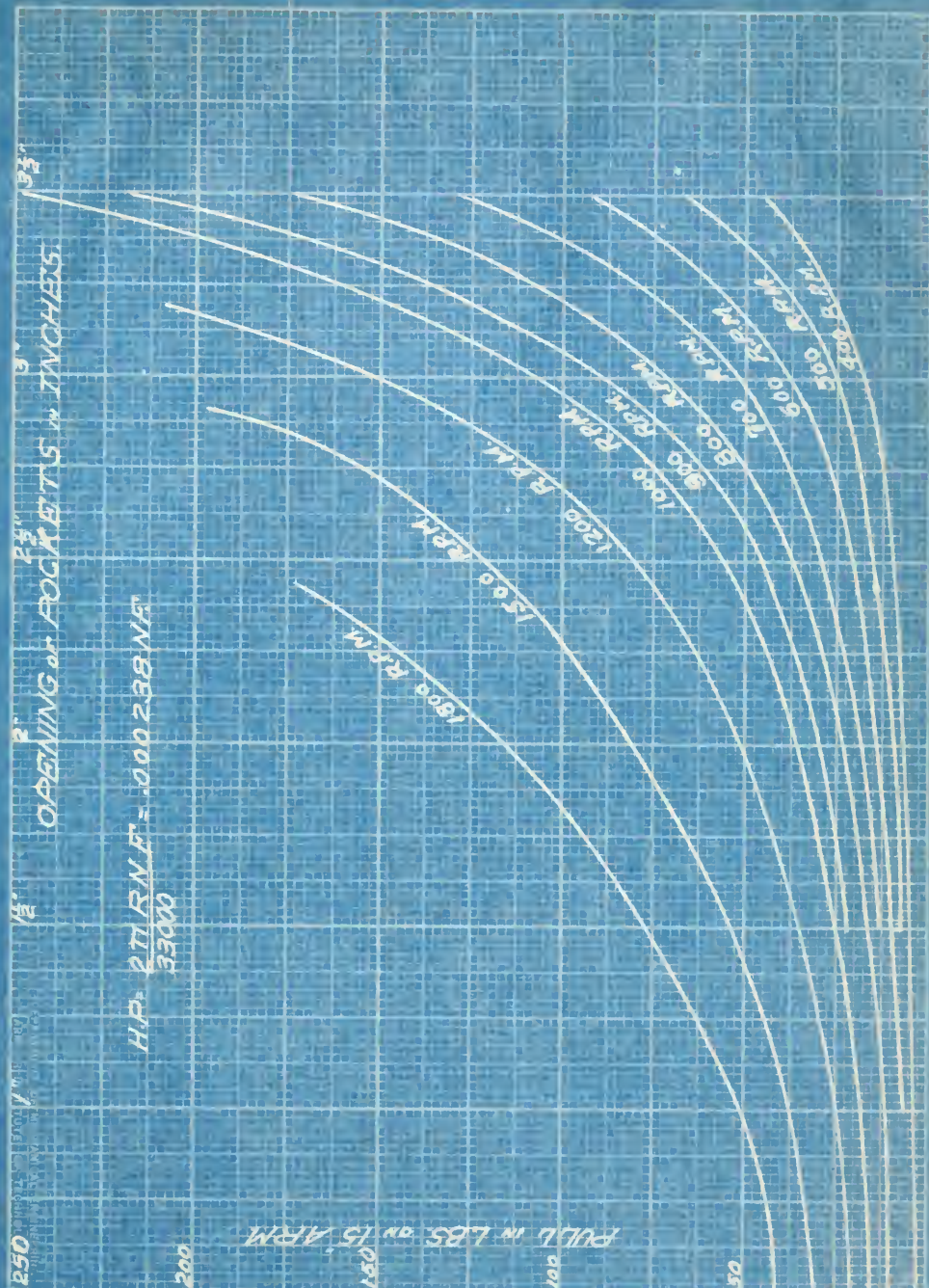
This would allow all compartments to have the same filling of water and thus offer the same power absorbing properties with other things being equal. From the above discussion we may see where this work of developing the hydraulic dynamometer may be carried on.

There are a number of hydraulic dynamometers on the market used for absorbing the power developed by engines. Drawings of some of the various types may be found in the end of this thesis. The dynamometer shown on the accompanying photostat is manufactured by the Michigan Motor Specialties Co. This brake has one disc or impeller which varies from the one used in the investigation. This rotor is made up of one revolving body or impeller. This rotor has pockets cut on the outer periphery. These pockets slope in the direction of rotation of the impeller and thus have the tendency to scoop up the water. Also on the inner periphery of the casing in which this





MICHIGAN MOTOR SPECIALTY CO.
STANDARD 3"
HYD DYNAMOMETER
SCALE 1
AUGUST 2 1914
BY
BRANN 37



Development Of A Hydraulic Dynamometer.

impeller rotates we have pockets cut in a direction opposite to those on the rotor. The casing is enclosed on all sides by plates. These plates support two brass glands or bushings through which the impeller shaft extends. Stuffing boxes prevent the leakage of water from around the shaft. Between the casing and the impeller are two endless brass rings. By means of outside control we are able to change the position of these rings. This control is made by a hand wheel with a screwed shaft fastened to it. By turning this wheel we can move the rings in either direction. These rings control the area of the pockets and thus vary the resistance caused by the shearing action of the water between the pockets. Thus when these ring like shutters are closed or touch each other, the friction or resistance is reduced to a minimum. When they are wide open so as to expose the total area of the pockets, the dynamometer will then be able to

Development Of A Hydraulic Dynamometer.

absorb as high as 60 horsepower at a speed of 1000 R.P.M. On the outside of this casing there is attached a torque arm which measures 15" from the center of the brake shaft to the point of attachment to the balance. The casing and dynamometer are supported on two pedestals by the shaft to which the impeller is attached. This is not a point of advantage, because of the power consumed by friction of the shaft in the pedestal bearings. A better method of supporting the dynamometer is that used in the dynamometer used in the investigation.

The water is admitted into the dynamometer through a pipe tapped into the top of the casing. The water fills these pockets as they pass this supply pipe. The outlet for the water is primarily through a pipe tapped into the side plate of the casing. This pipe removes the water that has filled up the space between the impeller and the sides of the casing. Also there is an outlet pipe in the

Development Of A Hydraulic Dynamometer.

bottom of the casing which drains all the water from the casing as well as from the pockets. By means of valves placed in the inlet and outlet lines we are able to control the rate of flow of water through the casing and pockets. This permits of circulating sufficient water so as to keep the dynamometer from overheating.

The accompanying blueprint represents the characteristic curves for this type of brake when operating under various settings. These settings are the various openings of the pockets determined by the position of the movable brass rings. These curves are similar to those obtained from the smooth disc type of hydraulic dynamometer, and the electric and fan type of dynamometers.

Development Of A Hydraulic Dynamometer.

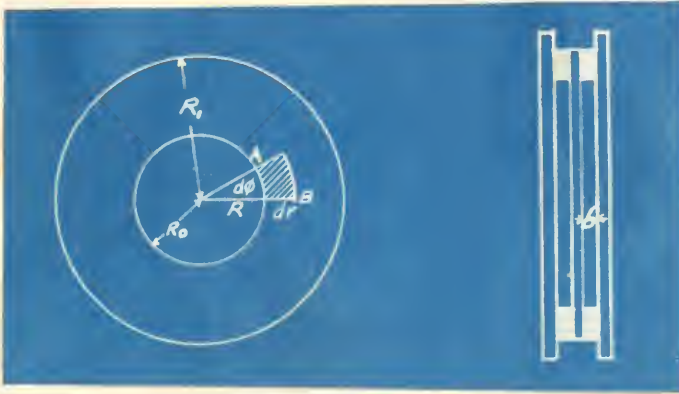
Formulae For Hydraulic Brakes.

The action or results that may be expected from any machine or engine may be expressed in most cases by a formula. A formula, when derived for such purposes, is supposed to give, within a reasonable allowance, the results that may be obtained by the machine when a certain given set of conditions is complied with.

The operation and results of this water dynamometer may be expressed by means of a formula when taken in accordance with the given conditions. These conditions under which the dynamometer may operate will determine the results obtained. Certain assumptions, although not exactly correct, must be made in order to place the fundamentals of the formula on a certain basis.

Development Of A Hydraulic Dynamometer.

Derivation Of A Formula.



Let us take an elementary area $A B$ on one face of a rotary disc. Let this area be part of a ring of water having a width equal to the distance between the rotary and stationary disc, and call it b . If we let the inner radius of the ring be R and the angle that bounds this area be $d\phi$, then the area AB is equal to $R d\phi dr$. The volume of this elementary unit is then $R d\phi dr b$. Let g be the weight of a unit volume of water. We then have the weight of this unit of water as $R d\phi dr b g$. Let the disc rotate with a speed of N revolutions per minute. The centrifugal force of a rotating

Development Of A Hydraulic Dynamometer.

mass is given by the formula;

$$F = \frac{M \times V^2}{R}$$

V is the linear velocity and equals $2\pi RN$

R is the radius of the circular motion

M is the mass of the body and equals the weight of the body divided by the acceleration of gravity.

Substituting these valuss in the formula for the centrifugal force, we have,

$$F = \frac{W \times 4\pi^2 R \times N^2}{32.2 \times 3600}$$

But we saw that the weight of the unit of water was equal to $b \times R \times d\phi \times dr \times g$, and substituting in the formula,

$$F = \frac{b \times g \times R^2 \times d\phi \times dr \times 4\pi^2 \times N^2}{32.2 \times 3600}$$

By putting in all numerical values we get

$$F = .0213 \times b \times R^2 \times d\phi \times dr \times N^2$$

Now since water pressure at a point is equal in all directions we can say that this is the pressure causing the increase in friction on the sides of the discs and between the layers

Development Of A Hydraulic Dynamometer.
 of water. Also this pressure acts on the elementary area AB. Now let f represent the coefficient of resistance. We will not call f the coefficient of friction, because we have other actions entering into this besides friction. Then F is the total resistance on the area A B, and is equal to

$$F = .0213 \times b \times R^2 \times d\phi \times dr \times N^2 \times f.$$

Now this force F , which is a retarding force, acts at the radius R and so exerts a torque

$$F R = .0213 \times b \times R^3 \times d\phi \times dr \times N^2 \times f$$

Now if sum up all such expressions for the torque on the area of the ring we have the integral

$$T = .0213 \times b \times N^2 \times f \int_{R_0}^{R_1} \int_0^{2\pi} R^3 d\phi dr$$

After carrying out the double integration we have the expression,

$$\begin{aligned} T &= \frac{.0213 \times b \times N^2 \times f \times 2\pi}{4} (R_1^4 - R_0^4) \\ &= .0335 \times b \times N^2 \times f (R_1^4 - R_0^4) \end{aligned}$$

This action we notice takes place on one side of the disc only, and since the water acts the

Development Of A Hydraulic Dynamometer.

same on two sides, we have the total torque per disc equal to

$$T_d = .067 \times b \times N^2 \times f (R_i^4 - R_o^4)$$

If the dynamometer has D discs, then the total torque for the dynamometer is

$$T = .067 \times b \times N^2 \times f \times D (R_i^4 - R_o^4)$$

Now if the length of the brake arm on the dynamometer is L feet long and the pull on the scale is P pounds, then PL is also the torque on the dynamometer and thus,

$$P L = b \times N^2 \times f \times D \times (R_i^4 - R_o^4) (.067)$$

This is the general formula for this type of brake. If we embody all numerical values into a constant K, our formula comes down to the simple form

$$P L = K \times N^2 \times D \times (R_i^4 - R_o^4)$$

This particular brake had eight discs. Replacing D by eight in the formula we have

$$P L = K \times N^2 \times (R_i^4 - R_o^4)$$

The formula for horsepower is given as

$$H.P. = \frac{2 \pi N \cdot R \cdot F}{33000}$$

Development Of A Hydraulic Dynamometer.
 Substituting the value for the torque in
 this horsepower formula,

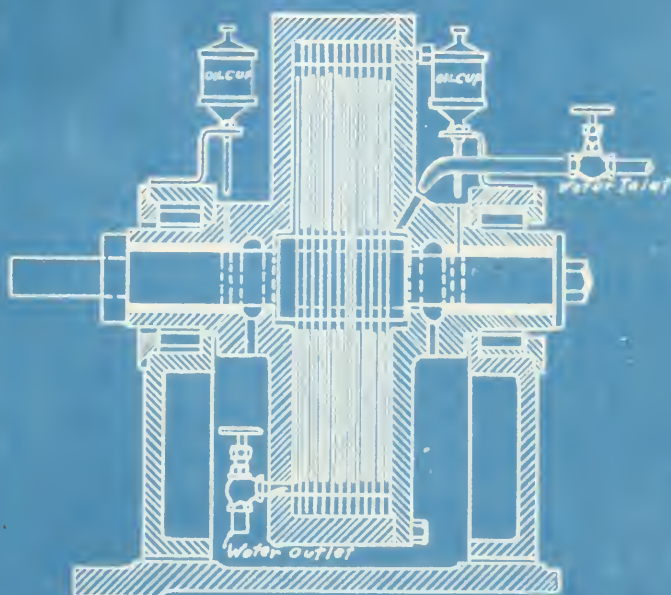
$$\text{H.P.} = K N^2 (R_1^4 - R_0^4) \frac{2 \pi N}{33000}$$

Again combining all numerical values into a
 constant K we have

$$\text{H.P.} = K N^3 (R_1^4 - R_0^4)$$

R_1 and R_0 are in feet.

The results obtained by making substitutions
 in the formula were not consistent with those
 found by experiment. This is due to other
 complications taking place within the brake
 that are not brought out in the formula. The
 formula will hold only where a new constant is
 taken for each filling of the dynamometer
 barrel. When the values, obtained by experiment,
 were plotted on logarithmic paper it was found
 that in almost all cases the horsepower
 varied with the cube of the speed. This fact
 is brought out in the derived formula. Thus
 when the proper constant is used in the
 formula for any filling of water, we can



SECTION THROUGH BRAKE

Development Of A Hydraulic Dynamometer.

obtain, to a certain extent, the torque that this brake will hold at any accompanying speed. The constant K must be found by experiment. This was found to vary too much to give any decisive value. Thus this formula is not as reliable as some of those given in this thesis.

A formula, similar to the one derived, was published in the May, 1916, issue of the "POWER" magazine. A sketch of the brake is also shown. The formula was given for the pull at the end of an arm L feet long.

$$P = \frac{0.145 D N^2 (R_1^4 - R_0^4)}{L}$$

From the above formula we can obtain the horsepower formula, by placing the value of P in

$$H.P. = \frac{2\pi N L P}{33000}$$

P is the pull in pounds on the scale.

L is the scale arm in feet.

D is the number of revolving discs

R_1 and R_0 are the radii of the water ring.

N is the revolutions per minute.

Development Of A Hydraulic Dynamometer.

The constant was not derived but obtained experimentally after the brake was constructed. There is a close similarity between the formula given here and the one previously derived. This constant includes a number of numerical values. This brake had twelve revolving discs, and at a speed of 1200 R.P.M. could be adjusted to hold as low as $1/2$ H.P. Also after a number of the discs were removed, a lower power could be carried. By increasing the amount of water in the barrel 25 H.P. were absorbed at 1200 R.P.M. This goes to show how a dynamometer of the type mentioned may be used for any conditions.

The dynamometer used by the writer in his investigations carried only about 16 H.P. at about 1100 R.P.M. This brake had 8 discs on the revolving shaft. Thus, in comparison with the above mentioned brake, they both have about the same capacity in proportion to the number of revolving discs.

Development Of A Hydraulic Dynamometer.

An article by Winslow H. Herschell appeared in the August 1916, issue of "The ENGINEERING NEWS" concerning the testing of a steam turbine with the aid of a water brake. The brake, used in this test, had 6 smooth discs, having a diameter of 24". There was a space of 1/2" between the revolving and the stationary discs. There were 1 1/4" holes in the sides of the stationary discs to allow circulation of the water through the compartments. The torque arm measured 5 feet 3 inches from the center of the shaft to the connection with the scale. With this length of arm the formula,

$$H.P. = \frac{2\pi R N W}{33000}$$

reduces to

$$H.P. = \frac{W N \times 33}{33000} = \frac{W N}{1000}$$

where W is the pull on the scale in pounds, and N is the revolutions per minute.

In order to prevent the water in the dynamometer from becoming too hot and turning

Development Of A Hydraulic Dynamometer.

into steam, we must circulate a certain amount of water through the barrel of the dynamometer. The necessary amount of water needed per minute, may be given by the formula,

$$Q = \frac{\text{B.H.P.} \times 33000}{778 (t_2 - t_1) 8.32}$$

where Q is the rate of flow in gallons per minute, B.H.P. is the horsepower that the brake is absorbing and 778 is the mechanical equivalent of heat. t_2 and t_1 are the outlet and inlet temperatures of the water. 8.32 is a factor converting pounds of water to gallons.

The water was supplied to the dynamometer at a point near the center of rotation of the revolving discs. The reason for this is the centrifugal action of the water during the rotation of the discs. The pressure at the center of the dynamometer is small and therefore this would seem to be the logical point at which to admit water. A constant head of water was kept on the brake so that the compartments had at all times a constant flow

Development Of A Hydraulic Dynamometer.

of water. This was accomplished by placing a tank over the dynamometer and running a pipe from the tank to each cell of the dynamometer.

A formula, derived by Roetscher, was used in connection with this brake. This formula was obtained by experiment, and proved Froude's statement;" that of two dynamometers of different sizes, their respective moments of reaction at the same R.P.M. vary as the fifth power of their respective dimensions of the submerged surface!" Roetscher's formula is;

$$\text{B.H.P.} = \frac{D^{5.366} N^{2.66}}{4.704 \times 10^{16}}$$

B.H.P. is the maximum horsepower that can be absorbed by one disc. D is the diameter of the rotating disc in centimeters. N is the R.P.M.

The brake that Roetscher used in his experiments had perforated discs. Thus by using his constants we would expect too high values for a dynamometer with smooth

Development Of A Hydraulic Dynamometer.
discs. By actual test of this steam turbine
by Herschell, 1100 horsepower at a speed of
3600 R.P.M. was obtained; while by substitution
made in the formula, 1380 horsepower was
obtained at this speed. With the brake used,
the horsepower was varied from as low as 49
to 1326 horsepower with good results.

Another formula based upon the theory,
that the resistance offered by a dynamometer
varied with the square of the angular velocity
and the fifth power of the radii of the ring
of water between the discs, was found in
Gibson's "Hydraulics". Thus assuming the square
law, we have the resistance of each face

$$\omega^2 2\pi f \int_{r_2}^{r_1} r^4 dr$$

f is the coefficient of resistance, and is
equal to about .0045 for rough surfaces. ω is
the angular velocity in radians per second.
 r_1 and r_2 are the outer and inner radii of the
submerged portion of the discs in feet.

Development Of A Hydraulic Dynamometer.

Now if we integrate the above expression we have the resistance is equal to

$$\frac{2\pi f\omega^2(r_1^5 - r_2^5)}{5}$$

Let the brake have n number of discs. Then there will be 2n number of faces, and so the total resistance offered by the brake is

$$\frac{4nf\pi\omega^2(R_1^5 - R_2^5)}{5}$$

from this we get the horsepower absorbed is equal to

$$\frac{4nf\pi\omega^2(R_1^5 - R_2^5)}{5 \times 550}$$

Thus in this formula we have a coefficient f which depends upon the nature of the discs. This value f must be determined by experiment for a given type of brake so that it may be substituted in the formula when a brake of this type is to be designed.

To show the correctness of this formula, values were substituted in the formula and results somewhat near those found from test were obtained.







CURVES FOR WATER DYNAMOMETER SHOWING THE EFFECTS OF SLOTTING THE DISCS

